Results of the Preliminary Analyses of Asteroid Ryugu Regolith Samples Returned by the Hayabusa2 Mission

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Introduction: The Hayabusa2 spacecraft returned 5.5g of regolith material from asteroid 162173 Ryugu in December 2021. The samples were maintained in near-vacuum conditions up to and even during many analyses, a factor that was critical for comparisons of Ryugu lithologies to meteorites because of ubiquitous terrestrial alteration of the latter. Observations of asteroid Ryugu by the Hayabusa2 spacecraft found that it is spinning, top-shaped rubble pile, formed from re-accretion of a (probably) small subset of fragments from a disrupted parent asteroid. Samples retrieved from Ryugu by the spacecraft during two brief touchdowns were expected to contain a record of this history, including the formation and early evolution of the parent body, its subsequent impact destruction and partial re-accretion, and later space weathering. The composition of Ryugu was expected to be similar to that of naturally-heated Ivuna-type carbonaceous chondrite meteorites (CI chondrites), based on ground- and spacecraft-based spectroscopy. Six preliminary examination teams investigated the formation history of Ryugu through laboratory analysis of the returned samples over the past 18 months. Specifically, we sought to determine (1) when and where in the Solar System the parent asteroid of Ryugu formed; (2) the original mineralogy, bulk elemental abundances, and chemical compositions of the accreted materials; (3) how these materials evolved through chemical and physical processing of the parent asteroid; and (4) how the parent asteroid was disrupted during impact and reaccumulated into Ryugu. This brief report mainly summarizes results from the mineralogy and petrology subteams [1&2], although results of the composition and isotope subteams are also mentioned (see [3] for an overall summary). To address these issues, we analyzed numerous Ryugu particles up to ~8 mm in size.

Results: The majority of Ryugu samples are nearly identical to unheated CI1 chondrites, with additional related lithologies. This was a surprise as heated samples were expected based on prior spectroscopy of the Ryugu asteroid. We found CO_2–bearing brine aqueous fluid inclusions in a pyrrhotite crystal which had been pre-located by X-ray Computed Tomography (XRCT), indicating that the parent body formed in the outer Solar System. Remanent magnetization was detected in magnetite using electron holography, implying that the solar nebula might still have been present when those magnetite crystals formed on the original parent body. Muon analysis revealed the abundances of light elements, including carbon, nitrogen,

sodium, and magnesium, whose abundances relative to silicon are similar to those in CI chondrites, whereas oxygen is deficient by ~20% compared with that in CI chondrites. This result has important implications as the CI bulk composition is usually used as a proxy for the nebular bulk composition.

As with the CI1 meteorites, the most common minerals in Ryugu samples are saponite and serpentine family minerals, Mg-Ca-Fe carbonates, hydroxyapatite, pyrrhotite, pentlandite, and magnetite. Minor phases include a still enigmatic Na-phosphate. There is also rare olivine and low-Ca pyroxene and other high-temperature materials, including CAI, all being smaller than 100 mm. This mineral assemblage indicates widespread aqueous alteration on the original parent body. The collected Ryugu samples are breccias, as expected and hoped. Some Ryugu fragments have a different mineralogy, and while still containing mainly phyllosilicates (some poorly crystalline) also include a 10-fold higher quantity of anhydrous silicates (mainly olivine and pyroxene), as well as amorphous silicates, Ca carbonate (i.e much less Mg-Fe carbonate), phosphides, pyrrhotite, pentlandite, and magnetite. Micron-sized round objects containing poorly-crystalline hydrous silicates and tochilinite are present – these resemble objects called “glass with embedded metal and sulfides” (GEMS) that are abundant in anhydrous chondritic interplanetary dust particles but very rare in meteorites. This lithology indicates significantly less aqueous alteration than the major Ryugu lithology, providing a clearer window onto the precursor mineralogy of the Ryugu parent body than has been provided by CI chondrite meteorites. We measured mechanical and thermal properties of the Ryugu samples and found that they are similar, but not identical, to CI chondrites. Numerical simulations of the thermal-chemical history and impact disruption processes of the Ryugu parent asteroid were performed by incorporating the physical and mineralogical properties and appropriate water/rock ratios. The relative chronologies of these processes were also determined.

Ryugu samples were returned to Earth in a sealed container, preventing immediate exposure to the terrestrial atmosphere. Despite these efforts alteration of the samples was apparent as time passed, but these changes could be tracked and carefully documented. Thus, sulfates and iron oxyhydroxides that are growing among the samples are definitively known to be of terrestrial origin. We had suspected this would be the case and an important component of the sample preliminary examination was to search for and observe this process, which is obviously critical to understanding the indigenous mineralogy of Ryugu.

Conclusions: The Hayabusa2 Preliminary Examination teams proposed that Ryugu’s parent asteroid formed ~1.8 million to 2.9 million years after the beginning of Solar System formation, in the outer Solar System, where water and CO_2 were present as ice. It acquired a water ice/rock mass ratio

in the range of 0.2 to 0.9. In this region, material formed at low temperatures is dominant, whereas material of high temperature origin is rare. In the interior of the parent asteroid, radioactive heating caused the water ice to melt at ~3 million years; water-rock reactions then gradually changed the initial anhydrous lithology to one that was largely hydrous over the next several million years. Less material was aqueously altered than has been found in the CI chondrite meteorites. An impact occurred ~1 billion years ago, disrupting the parent asteroid. Some fragments, probably originating away from the impact point, then reassembled to form Ryugu. Returning the collected samples to Earth in a “sealed” capsule and excluding (to the fullest degree feasible) interaction with the terrestrial atmosphere significantly slowed terrestrial alteration and rendered this process transparent. This precaution is obviously essential for all future astromaterial sample return missions.

References:
[1] Nakamura et al 2022. *Science* **377**, 10.1126/science.abn8671.
[2] Noguchi et al. 2023. *Science Advances*, in press.
[3] Tachibana et al. 2022. *Science* **375**, 1011-1016.